

12
13

INFRARED WAVEGUIDE MODULATORS AT MICROWAVE FREQUENCIES

ADA 015674

SEMI-ANNUAL TECHNICAL REPORT
PERIOD COVERED :
25 MARCH 1975 TO 25 SEPTEMBER 1975

CONTRACT NO. NO0014-73-C-0087

SPONSORED BY

ADVANCED RESEARCH PROJECTS AGENCY
ARPA ORDER NO. 1860, AMENDMENT NO. 6

DDC
RECEIVED
OCT 14 1975
A

UNITED TECHNOLOGIES
RESEARCH CENTER

EAST HARTFORD, CONNECTICUT 06108



UNITED
TECHNOLOGIES™

DECLASSIFICATION STATEMENT
Approved for public release
Distribution Unlimited

CATEGORY FOR 15		WHITE BOXES <input checked="" type="checkbox"/> DARK BOXES <input type="checkbox"/>
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31		
32		
33		
34		
35		
36		
37		
38		
39		
40		
41		
42		
43		
44		
45		
46		
47		
48		
49		
50		
51		
52		
53		
54		
55		
56		
57		
58		
59		
60		
61		
62		
63		
64		
65		
66		
67		
68		
69		
70		
71		
72		
73		
74		
75		
76		
77		
78		
79		
80		
81		
82		
83		
84		
85		
86		
87		
88		
89		
90		
91		
92		
93		
94		
95		
96		
97		
98		
99		
100		

UNITED TECHNOLOGIES RESEARCH CENTER

EAST HARTFORD, CONNECTICUT 06108

14 UTRC/

R75-922241-1

9

Sixth Semi-Annual Technical Report, no. 6, 25 Aug 72-
25 Aug 76,

6

Infrared Waveguide Modulators at
Microwave Frequencies.

by

10

P. K. Cheo, M. Gilden, and R. Wagner
United Technologies Research Center
East Hartford, Connecticut 06108

11

30 Sept 1975

12

34 P.

Principal Investigator - P. K. Cheo (203) 565-4297

Prepared for the Office of Naval Research

Contracting Officer: Dr. M. White

15

NO0014-73-C-0087, ARPA Order-1860
Contractor Modification No. P00003 - \$437,488

25 August 1972 to 25 August 1976

Sponsored by

Advanced Research Projects Agency
ARPA Order 1860, Amendment No. 6

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the U.S. Government. Reproduction in whole or in part is permitted for any purpose of the U.S. Government.

DN

409 252

TABLE OF CONTENTS

	<u>Page</u>
1.0 TECHNICAL REPORT SUMMARY.....	1-1
1.1 Program Objectives.....	1-1
1.2 Major Accomplishments.....	1-1
1.3 Future Work.....	1-2
2.0 HIGH POWER IR WAVEGUIDE MODULATORS.....	2-1
2.1 Introduction.....	2-1
2.2 Fabrication Techniques.....	2-3
2.3 Optical Transmission Characteristics.....	2-9
3.0 MICROWAVE CHARACTERISTICS OF IR WAVEGUIDE MODULATORS....	3-1
3.1 Introduction.....	3-1
3.2 Studies of Microstrip Transmission Lines.....	3-2
3.3 A Broadband Modulator Design.....	3-4
4.0 OPTICAL AND MICROWAVE INTERFACE.....	4-1
4.1 Introduction.....	4-1
4.2 Waveguide Modulator Assembly.....	4-1

1.0 TECHNICAL REPORT SUMMARY

1.1 Program Objectives

The long-range objective of this program is to develop an efficient and reliable ultra-wideband waveguide modulator for CO_2 lasers that will be useful for high resolution, imaging optical radars and high-data-rate optical communication systems. Efficiency and reliability are obtainable by using integrated optics technology.

During the reporting period (April 1975 to September 1975), major objectives are: (1) to develop techniques that will improve the quality and strength of the infrared waveguide structure, (2) to establish the relative advantages of grating and prism couplers, and (3) to establish the micro wave characteristics of microstrip modulator configuration. These developments are essential for the generation of the predictable (Ref. 1) level of sideband power at 16 GHz.

1.2 Major Accomplishments

During the reporting period, we have experimentally established all three above mentioned objectives. The first accomplishment involves the improvement of techniques for fabricating bonded-down thin GaAs slab waveguides on optically flat copper base plates. This development provides the necessary strength to the waveguide structure which allows the use of two pressed-down Ge prisms as the input/output couplers.

The second accomplishment involves the achievement of at least a factor of ten enhancement in optical transmission through the bonded-down waveguides by using prism couplers from previously reported measurements (Ref. 1) which were made on free-standing waveguides with two grating couplers. Finally, techniques have been developed to feed Ku-band microwave power into the GaAs thin-slab via a microstrip transmission line. Both the coaxial and step transformer types of microwave couplers have been considered. The former has been experimentally tested and will be used in the interim experiments for sideband power generation. The latter has been designed and its characteristics shall be extensively studied with particular emphasis on its bandwidth and linearity.

In a recent experiment using germanium prism couplers to feed the energy into and remove it from the waveguide, more than 3-W output was obtained from an input CO_2 laser beam (TEM_{00}) of 6 W, a transmitted power previously unattained with this

type device. Results indicate that our present waveguide structure is capable of handling optical powers in the tens of watts. A similar structure has previously been tested with microwave power up to 100 watts.

The waveguide strip is optically polished and bonded to an optically polished copper block. Ion-beam milling is used for the final thinning of the GaAs bulk material to the desired thickness (typically 25 microns). The thickness variation over the entire length (>4 cm) of the waveguide is less than one micron. A rugged device is formed, which permits the use of the most efficient prism couplers. The copper block forms the ground plane of the microwave modulator, which is designed to operate in the 10 to 18 GHz region. The copper is a good heat sink for both optical and microwave power.

1.3 Future Work

Work is in progress to generate sideband power at 16 GHz in the range from 10 mW to 100 mW by using 25 micron thick GaAs waveguides bonded onto copper blocks. Optical couplers will be Ge prisms which are either pressed against or bonded onto the waveguide. Microwave power will be fed into the waveguide from the center of the microstrip. This modulator is designed in accordance with the standing wave configuration (Ref. 2) which should provide the greatest modulation efficiency provided that the loss of the transmission line is small ($\lesssim 1$ dB). The measured loss of this microstrip line is 0.75 dB/cm.

Work will be continued to improve optical waveguide structures. Of particular importance is the transmitted optical beam quality as well as the highest power. This work involves further refinement of waveguide fabrication procedures and characterization techniques of material defects.

Finally, work will be directed toward the attainment of a laboratory model of a broadband traveling wave microstrip modulator for CO_2 laser radiation which is capable of generating several hundred milliwatts of frequency chirped sideband power at 16 GHz.

2.0 HIGH POWER IR WAVEGUIDE MODULATORS

2.1 Introduction

Extensive measurements of optical coupling of infrared waveguides have previously been made on a number of the "free-standing" GaAs thin-slab waveguides with two ion-beam milled phase grating couplers. Optical transmission through these waveguides were consistently found to be much less than the anticipated value of 20 percent by about a factor of 5. On the other hand, the use of a prism coupler with these waveguides increases optical transmission relative to that achieved with grating couplers much more than anticipated. Furthermore, the use of a prism as the input coupler enhances the transmission more than its use as the output coupler. The relative merits of optical couplers, prism vs. grating, are summarized in Fig. 1. P_o and P_t are the incident and the transmitted laser power, respectively. Three different types of coupling experiments as shown in (a), (b) and (c) were made on the same waveguide. In each case the beam size was adjusted to achieve aperture matching. By replacing the input grating with a prism, the optical transmission is enhanced by a factor of 10, which is 5 times as much as expected. Although the propagation length in cases (b) and (c) has been decreased from that of case (a), the difference in length certainly cannot account for the large change in transmission. The results of (b) and (c) indicate that the coupling efficiency is more sensitive to the input coupler characteristics than to those of the output coupler.

The disagreement between theoretical (Ref. 3) and experimental results for grating coupling efficiency is not well understood. Similar results have been obtained independently by others (Ref. 4). A possible explanation for this discrepancy is that previous calculations are based on a perturbation theory (Ref. 3) that assumes that the grooves of a grating coupler do not cause a significant change in waveguide characteristics. This assumption may not be justified under the practical situation where grooves, in fact, can introduce large defects in a waveguide that will cause significant reduction in coupling efficiency.

Since April, 1975, the program has been redirected toward the use of prism couplers. As a result, a significant milestone for this program has been reached. We have obtained more than 3 watts transmitted CO_2 laser power through the GaAs waveguides by using Ge prisms as the couplers. The measured input coupling efficiency exceeds 60% by assuming a 100% output coupling efficiency. To accommodate two prisms, the "free-standing" waveguides are not suitable because structural limitations are such that these thin-slab waveguides can easily be cleaved under pressure. Processes for strengthening these thin-slab waveguides have long been considered (Ref. 5), but not until very recently have we succeeded in obtaining reasonably good quality, bonded-down waveguides with the desired length (>4 cm) and the desired thickness uniformity ($\Delta t/t \lesssim \pm 2.5\%$ over the entire length of 4 cm). A 10 micron-thick copper film is applied to the polished GaAs surface before bonding onto an optically-flat copper block with a thin layer of indium. This copper film is needed primarily to reduce the microwave propagation loss. With these bonded-down waveguides, we have made extensive measurements of the optical transmission

RELATIVE MERITS OF OPTICAL COUPLERS

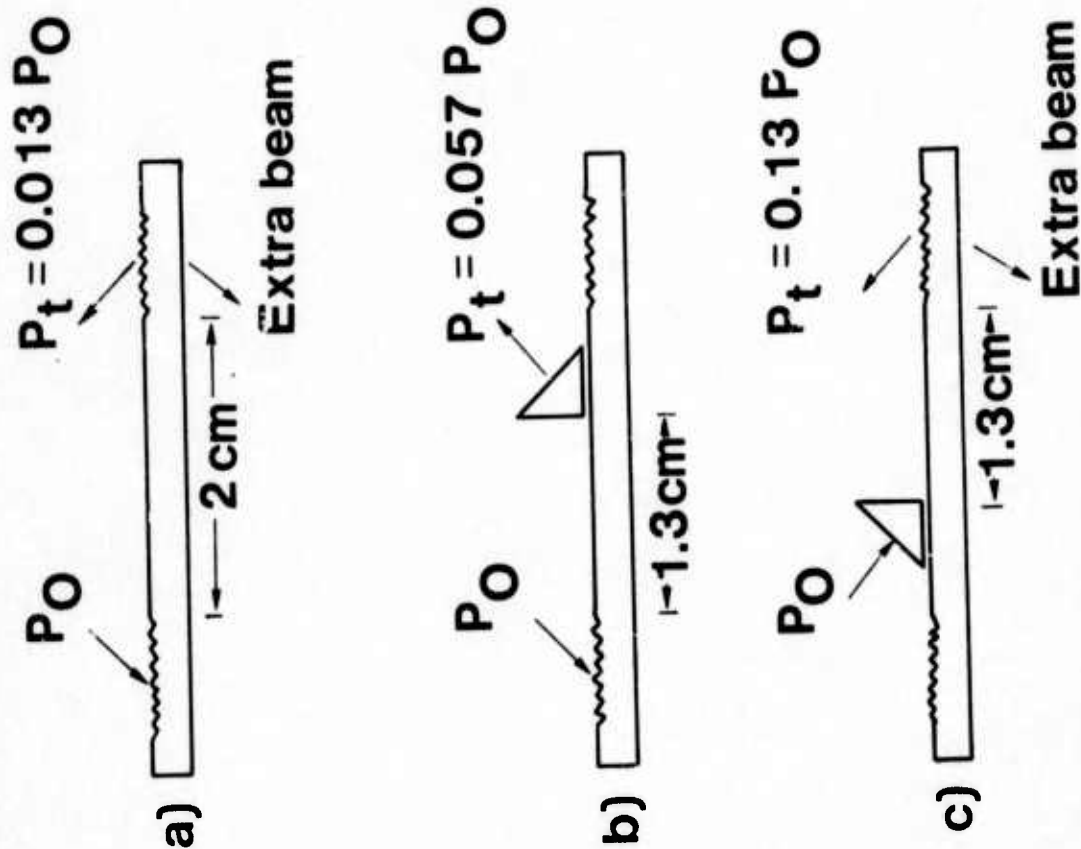


FIG. 1

R09-13-1

characteristics using two germanium prisms. In the following we shall describe the waveguide fabrication procedure in detail and discuss the experimental results on optical measurements.

2.2 Fabrication Techniques

2.2.1 High Power IR Waveguide Modulator Specifications

The success of this program depends solely on the ability to fabricate waveguides which will eventually approach the idealized waveguide configuration that can yield predictable results. Previous investigations (Refs. 1 and 2) indicate that bonded thin-slab waveguide is the best choice for our application. From studies (Ref. 2) of the broadband matching of microwave power into a GaAs filled mini-gap transmission line it was evident that more reproducible results can be achieved if the top and bottom copper electrodes were deposited onto the surfaces of the GaAs thin-slab with its bottom face bonded on a flat copper block, which forms the ground plane. A bonded waveguide also provides the necessary strength and rigidity to permit the use of prism couplers. The need for using prisms as optical couplers are evident from our previous studies (Ref. 1) of two grating couplers on free-standing GaAs thin-slab waveguides. Optical performance of the modulator structure with two gratings is rather discouraging. Optical transmission increases significantly when the input grating coupler is replaced by a prism. Only one prism coupler is all that the free-standing waveguide can afford. During this reporting period, work has been directed toward the development of bonded-down waveguide structures.

The specifications for the bonded-down GaAs waveguides are:

1. Thickness to be in the range of 20 to 30 μm .
2. Length to be greater than 4 cm.
3. Wedging to be less than 1 μm over 4 cm length.
4. Thickness of bonding layer to be uniform with a thickness not greater than 2 μm .
5. Surfaces of GaAs waveguides to be mirror-like finished.
6. Waveguides to be free from process-induced damage.
7. Edge rounding to be less than 1 μm .
8. Copper electrode thickness to be uniform and greater than twice of the skin-depth.
9. Copper supporting block to be optically flat and parallel to within 5 sec of an arc.

In the following section, we shall describe our method of fabrication and outline the processing procedure for accomplishing or approaching these specifications as listed above.

2.2.2 Method of Fabrication

High resistivity Cr-doped GaAs ingots in large size can be obtained from a number of vendors. Three major companies from which we have purchased materials are: Laser Diode Laboratory, Morgen and Texas Material Laboratory.

All materials used for waveguides have always been carefully characterized by performing the Hall measurement and etch-pit density evaluation before slicing into thin wafers at the orientation [100] plane. The thickness of these saw-cut wafers is typically at 15 mils. The typical wafer size is large enough to yield 3 (1 cm x 4.5 cm) rectangular waveguide modulators.

The first step in the fabrication procedure is to lap one face of the wafer which serves as the reference plane. This is accomplished by waxing the wafer on a flat copper block, which is fastened to the polishing jig, as shown in Fig. 2. This precision polishing jig was developed by Bennet and Wilson (Ref. 3 and 4), with a technique that can polish a single crystal specimen to a thickness of the order of 1 μ m, while maintaining the parallelism of the specimen without removing it from the mount. It consists of an outer holder into which a hardened steel sleeve has been pressed. Also attached to the holder are four steel legs, the ends of which are hardened and ride on the surface of the metal lapping plate. A piston runs inside the steel sleeve with a lapped sliding fit.

The piston is rigidly fixed to a 5 inch diameter backplate and this in turn is attached to a front mounting plate by means of three springs and three angular adjustment screws. The angular adjustment screws are used to correct the orientation of the mounting plate and the wafer with respect to the lapping surface. Pressure loading is accomplished by incorporating a compression spring between two collars, one fixed to the piston and the other screwed on to the outer holder. Lapping is accomplished by placing the jig with attached GaAs wafer in the polishing apparatus manufactured by Geoscience Corporation. The unique feature of this apparatus is that it provides a random walk agitation instead of the circular motion of most conventional polishing instruments.

Mirror-like finishing of the lapped face is accomplished by a gentle chemo-mechanical polishing through which only a few microns thick material is removed from this lapped face. A few microns polishing is not sufficient to remove the lapping-induced damages underneath the surface of the wafer, however, it does provide a mirror-like surface. Further removal of the material by as much as several mils in thickness is accomplished by using ion-beam milling at a slow rate. The advantage of using ion-beam thinning techniques over the chemo-mechanical polishing is that ion-beam milling can preserve the integrity of the surface flatness, whereas the chemo-mechanical thinning process always produces edge-rounding. The extent of surface distortion depends on the amount of removed material. Furthermore, chemo-mechanical polishing requires pressure-loading on wafer that often produces severe wedging difficulty. The amount of stress induced in the wafer by ion-beam is not known. Optical transmission measurements on ion beam trimmed waveguides indicate that propagation loss is caused primarily by the absorption of

PRECISION POLISHING JIG FOR GaAs WAVEGUIDES

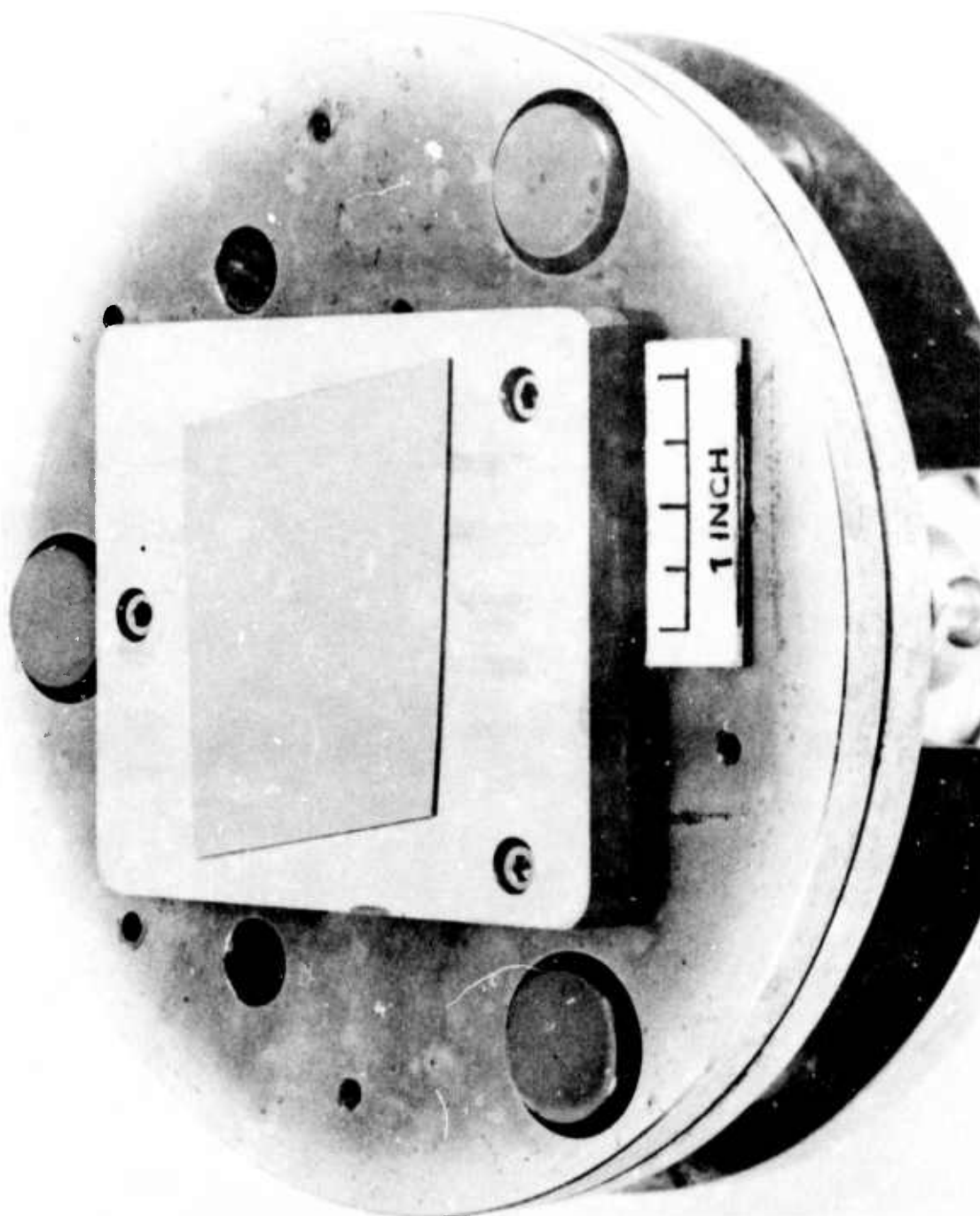
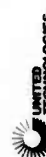


FIG. 2

RO9-178-3



metal electrodes rather than by the imperfections of the waveguides (more discussion on waveguide losses is given in Section 2.3).

This lapped and polished reference surface is now subject to vacuum deposition of 1 μm thick copper film, on which additional copper is electroplated to a total thickness of about 10 μm . This copper layer is sufficient to form the ground plane for microwave transmission at Ku-band. This ground plane is then photoetched with 1 cm x 4.5 cm rectangular pattern by the standard photolithographic technique. This pattern forms the actual waveguide configuration, and it must be oriented in line with the cleavage plane [110]. After photoetching these patterns, the wafer is scribed and then cleaved into waveguides, as shown in Fig. 3.

For bonding of these pre-thinned waveguides, both surfaces of waveguide and the copper block are coated with approximately one micron thick indium. The 1/4 inch thick copper block has been carefully grounded and lapped with both surfaces parallel to ≈ 5 seconds of an arc. This is at present time the limiting factor of the thickness uniformity of wedging of our waveguides. Techniques are being developed to overcome this limitation by refining our present gauging system. The new technique for monitoring thinning process relies only on the front surface of the copper block. The basic gauging system is a noncontact gauging device for highly polished surfaces. The probe (manufactured by Ames-Mercer with a trade name Hover-probe) is floating on its own cushion of air with remote electronic control system for rapid and accurate measurements of height variations to better than 0.1 μm .

The flat copper block with bonded GaAs wafer is mounted again to the precision polishing jig (Fig. 2). By similar lapping procedure, the other GaAs face is lapped from a typical thickness of 12 mils down to 2.5 mils. Similar thinning processes involving chemo-mechanical and ion-beam milling are used to bring the wafer thickness down to one mil. During these processes, waveguide thickness and thickness variation are monitored with the Hover-probe. The final thickness measurements are made with infrared spectrophotometer.

To complete the modulator fabrication the top face of the bonded waveguide must be processed with a properly designed microstrip copper electrode configuration. This is accomplished by vacuum deposition of a thin layer of copper in the region where microstrip is located. Other surface area is protected by a layer of photoresist, which leaves the only microstrip pattern exposed. Additional copper is introduced to the one micron thick microstrip by electroplating process to a thickness of about 10 μm . The fabrication process is completed by removal of photoresist and the excess thin vacuum deposited copper film. Figure 4 shows a finished waveguide modulator with a microstrip electrode on the top surface and a 10 μm copper film for the ground plane (invisible). This waveguide modulator is ruggedly bonded on a 1/4 inch thick copper block to provide the necessary strength and power dissipation capability.

METALLIZED GaAs WAVEGUIDES (PRE-THINNED)

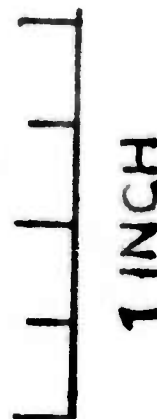
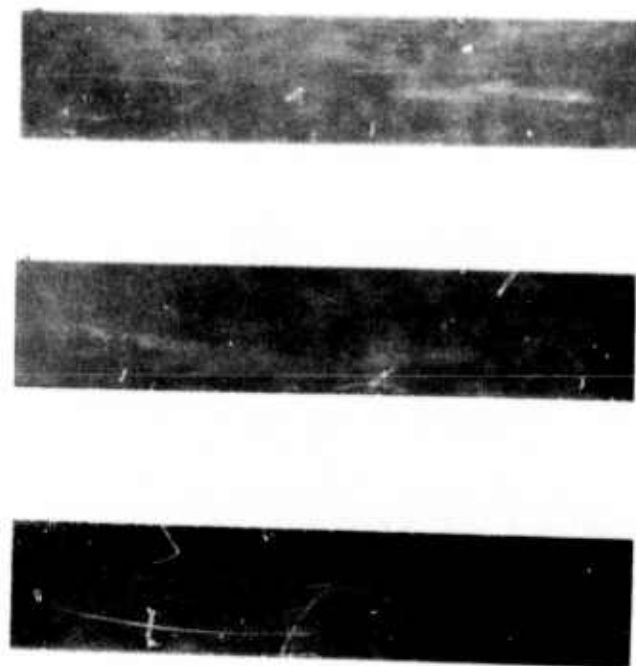
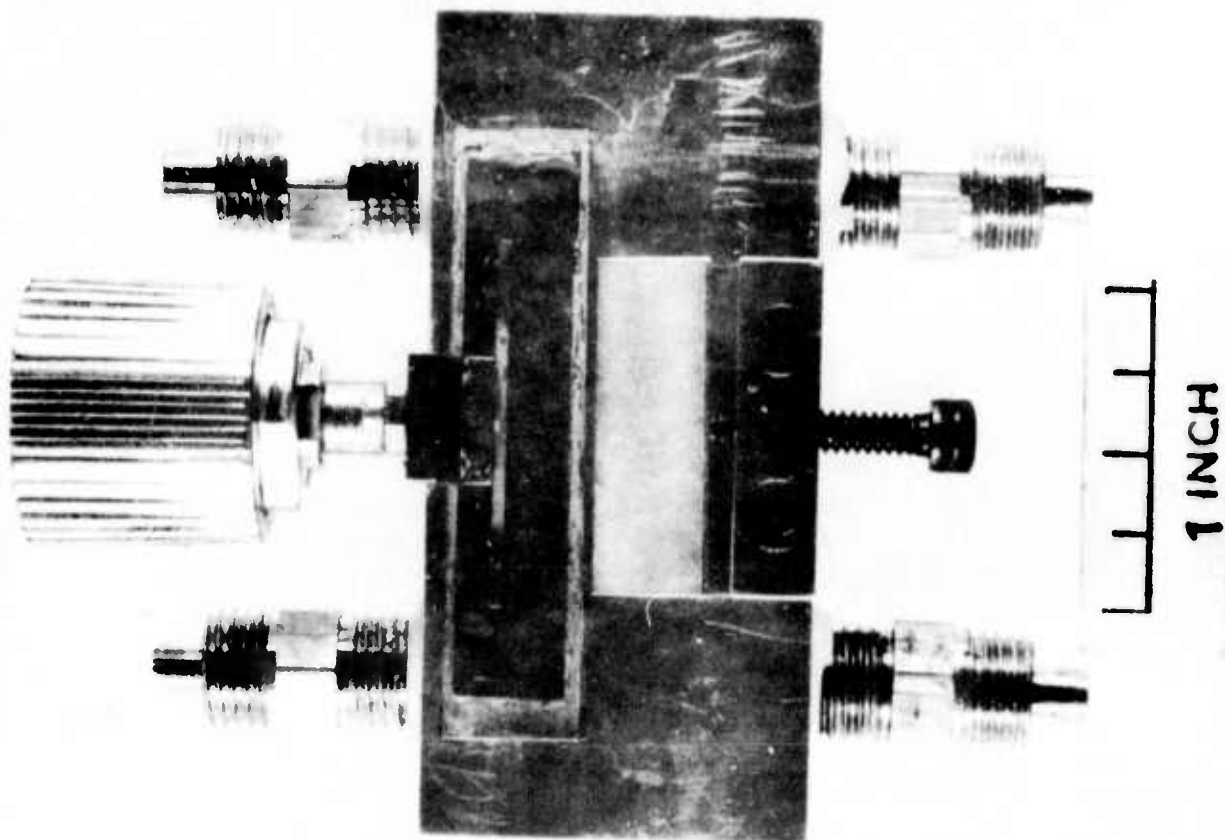


FIG. 3

RO9-178-2

WAVEGUIDE MODULATOR WITH A MICROSTRIP LINE



2.3 Optical Transmission Characteristics

Two major points which concerns the optical performance of the waveguide are (1) transmission efficiency and (2) transmitted beam quality. To a large extent, these two factors depend on the quality of waveguide and the prism couplers. The transmission efficiency is a function of the air gap spacing δ between the prism base and the upper boundary of waveguide. Detailed calculation by Tein and Ulrich (Ref. 8) indicates that the attenuation coefficient α of the coupler is given by

$$\alpha = e^{-2p_2\delta} \sin 2\phi_{12} \sin 2\phi_{32} / t_{\text{eff}} \tan\theta_1 \quad (1)$$

where

$$\begin{aligned} p_2 &= k[(\beta/k)^2 - 1]^{\frac{1}{2}} \\ t_{\text{eff}} &= t + 2/p_2 \\ \tan\phi_{12} &= \frac{p_2}{k} / [n_1^2 - (\beta/k)^2]^{\frac{1}{2}} \\ \tan\phi_{32} &= \frac{p_2}{k} / [n_3^2 - (\beta/k)^2]^{\frac{1}{2}} \\ \tan\theta_1 &= \frac{\beta}{k} / [n_1^2 - (\beta/k)^2]^{\frac{1}{2}}. \end{aligned}$$

The coupling efficiency is given by the well known formula

$$\eta = 2/\alpha \ell [1 - e^{-\alpha\ell}]^2 \quad (2)$$

where ℓ is the coupling length, which in general is dictated by the laser beam size. Assuming $\ell = 0.5, 1.0$ and 3.0 , we have computed η as a function of δ for a Ge ($n_3 = 4.0$) prism coupler on top of a GaAs ($n_1 = 3.275$) thin-slab ($t = 30 \mu\text{m}$) waveguide. The results are plotted in Fig. 5.

Figure 5 indicates that for optimum prism coupling, the air-gap spacing δ must be critically controlled. Typical δ values lie in the range from $0.05 \mu\text{m}$ to $0.5 \mu\text{m}$ depending on the order of the guided-wave mode. To excite lower order modes, higher pressure is required and can cause permanent damage to the bonded-down waveguides. Figure 5 also indicates that in the case of TE_0 mode, the optimum coupling length ℓ is greater than 3 mm . In the case of TE_1 mode, ℓ approximately equals to 1.8 mm for $\delta = 0.1 \mu\text{m}$. Another related problem is that it is essential to maintain a uniform gap spacing over the optimum coupling length. Imperfections in waveguides and in prism base in the form of wedging and rounding can reduce the coupling efficiency as well as the beam quality.

We have experimentally studied the optical transmission characteristics of a number of bonded-down waveguides with two germanium prisms. These two prisms were made in-house several years ago and are not of the best quality especially in regard to the prism bases which are convexed with at least 0.12 minutes of an arc. Since they were the only prisms available, they were used in all experiments presented in this report. Prisms with considerably improved quality will be used in future experiments.

Table I summarizes the optical transmission data accumulated to date. In all cases, the optical transmission through these waveguides via TE_0 mode is considerably reduced from that via TE_1 mode. This is due primarily to the size of the laser beam, or the coupling length l , used in these experiments. Because of other considerations involved in the design of microstrip circuitry at the Ku-band as discussed in greater details in Chapter 3 of this report. Laser beam diameter used in these measurements has been limited to a value in the proximity of 1 mm. For $l \leq 1$ mm, the coupling efficiency η for TE_1 mode is more than twice that for the TE_0 mode, as shown in Fig. 5.

From measurements of sample A with two different propagation lengths, it is noted that the propagation loss in a metal clad waveguide increases significantly with the mode order. These measured losses for various modes are in reasonably good agreement with our previously calculated (Ref. 9) loss values listed in Table II. Figure 6 is a plot of the electrode absorption coefficient α (cm^{-1}) as a function of waveguide thickness. Two data points as shown in Fig. 6 are obtained from the transmission measurements for sample D which has a total length of greater than 4 cm. The measured results agree remarkably well with the calculated values (Ref. 9) in spite of the fact that the calculation assumes a gold electrode instead of the copper used in our experiments. For this reason, it is desirable to utilize TE_0 mode particularly for a long modulator (i.e., $L \geq 3$ cm). This implies that the laser beam size must be increased substantially and consequently, the width of the microstrip must also be increased from the present value of 1 mm. This will effect the microwave coupling and propagation characteristics of the modulator. However, a tradeoff analysis will be made by taking into account for a wider propagation path, i.e., $W \sim 3$ mm.

From measurements of sample A, we obtain an extrapolated coupling efficiency for the TE_0 mode to be 20%, for the TE_1 mode to be 60%, and for the TE_2 mode to be 62% by assuming a 100% output coupling efficiency in all cases. These results indicate that the air-prism gap spacing is about 0.1 μm . In spite of the poor quality of the prisms, these results are for the first time encouraging and they are approaching the theoretical limit of 81%.

We have obtained more than 3 watts output laser power from these waveguides by using a 6 watt CO_2 laser input. At this power level, waveguides have been subjected to optical densities of greater than 7 kw/cm^2 , over a time period of several hours without damage. This indicates that the present waveguide structure is capable of handling high power and providing high transmission. At this power level (6 watts),

TABLE I

Summary of Optical Transmission Data

Mode	<u>Sample A (6-102-B1)</u> Thickness $\approx 28\mu\text{m}$		<u>Sample B (6-102-B2)</u> Thickness $\approx 30\mu\text{m}$		<u>Sample C (M-49271-1)</u> Thickness $\approx 26.5\mu\text{m}$		<u>Sample D (M-49271-2)</u> Thickness $\approx 26.5\mu\text{m}$	
	<u>Total Transmission (%)</u>		<u>Total Transmission (%)</u>		<u>Total Transmission (%)</u>		<u>Total Transmission (%)</u>	
	<u>$L=2.2\text{mm}$</u>	<u>$L=9\text{mm}$</u>	<u>$L=5\text{mm}$</u>		<u>$L=5\text{mm}$</u>		<u>$L=1.5\text{mm}$</u>	<u>$L=2.85\text{cm}$</u>
TE ₀	14.8	12.5	16.0		18.3		24.4	9.1
TE ₁	53.4	41.7	37.0		51.6		47.6	18.3
TE ₂	54.5	38.8	32.6		50.0		34.3	7.5
TE ₃	45.0	28.8	27.1		37.5		24.7	1.6
TE ₄	35.0	14.4	20.0		28.0		-----	-----

TABLE II

Electrode Absorption Coefficient a for TE_m Modes a (cm^{-1})

m	($t = 20 \text{ } \mu\text{m}$)	($t = 25 \text{ } \mu\text{m}$)	($t = 30 \text{ } \mu\text{m}$)	($t = 35 \text{ } \mu\text{m}$)
0	0.1092	0.0559	0.0323	0.0203
1	0.4405	0.2246	0.1300	0.0816
2	1.0068	0.5102	0.2937	0.1844
3	1.8322	0.9201	0.5271	0.3300
4	2.9572	1.4658	0.8344	0.5204

CALCULATED COUPLING EFFICIENCY

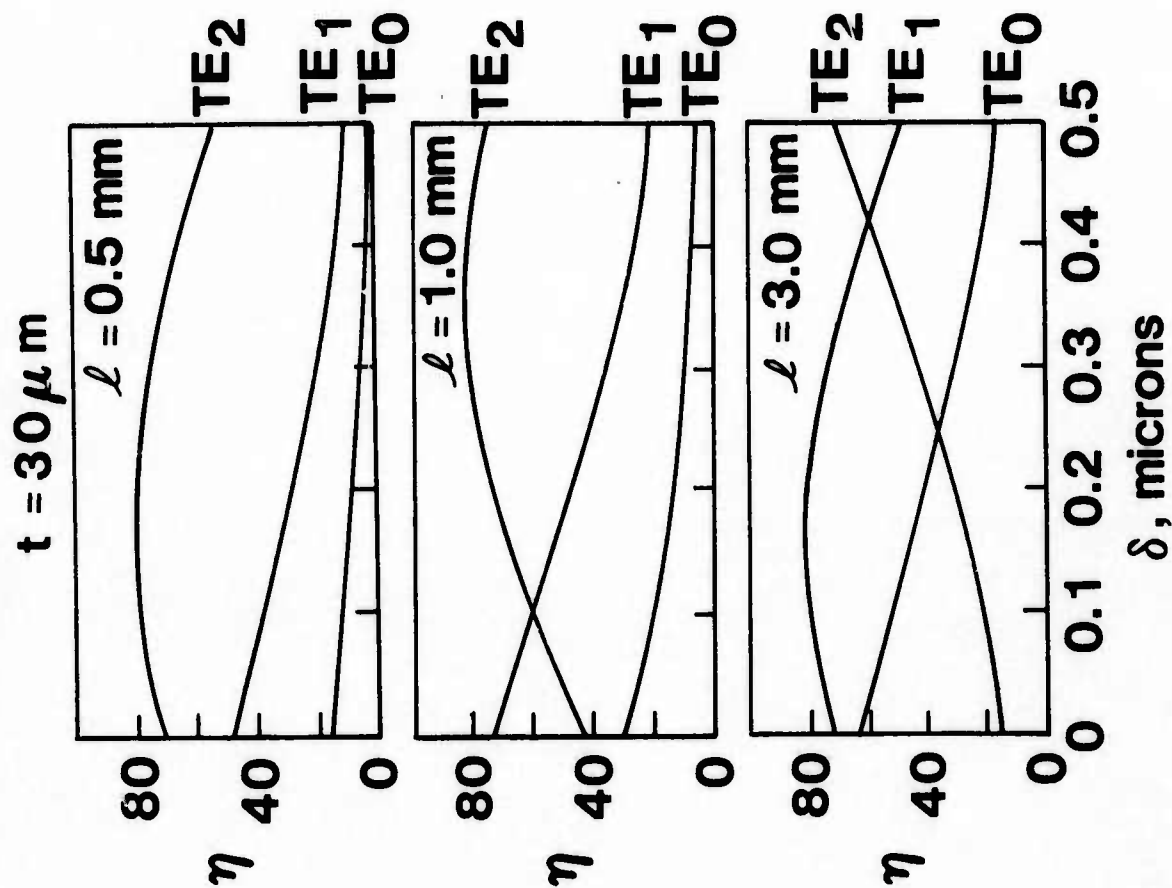


FIG. 5
ROS 57-1

ELECTRODE ABSORPTION CHARACTERISTICS

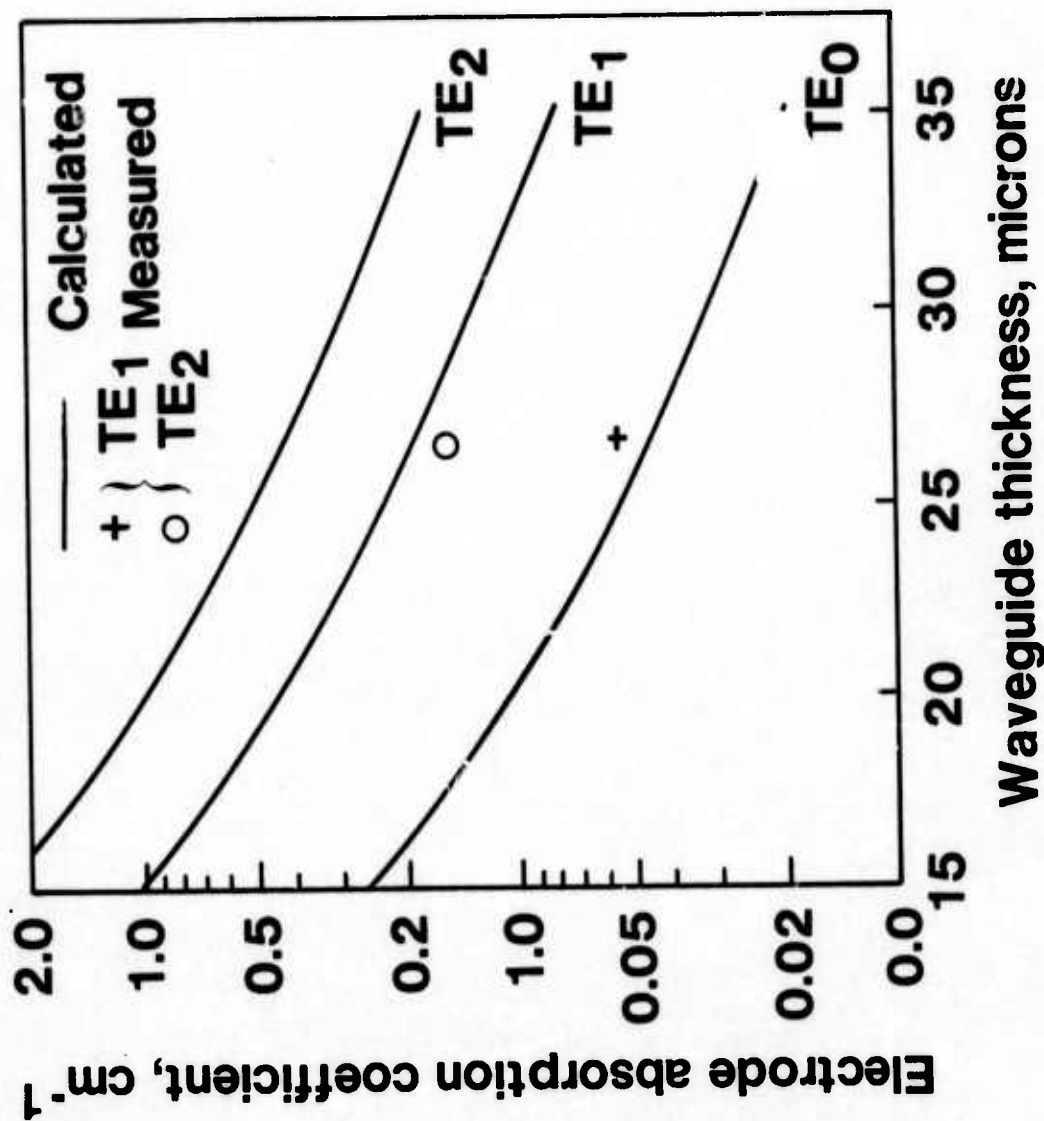


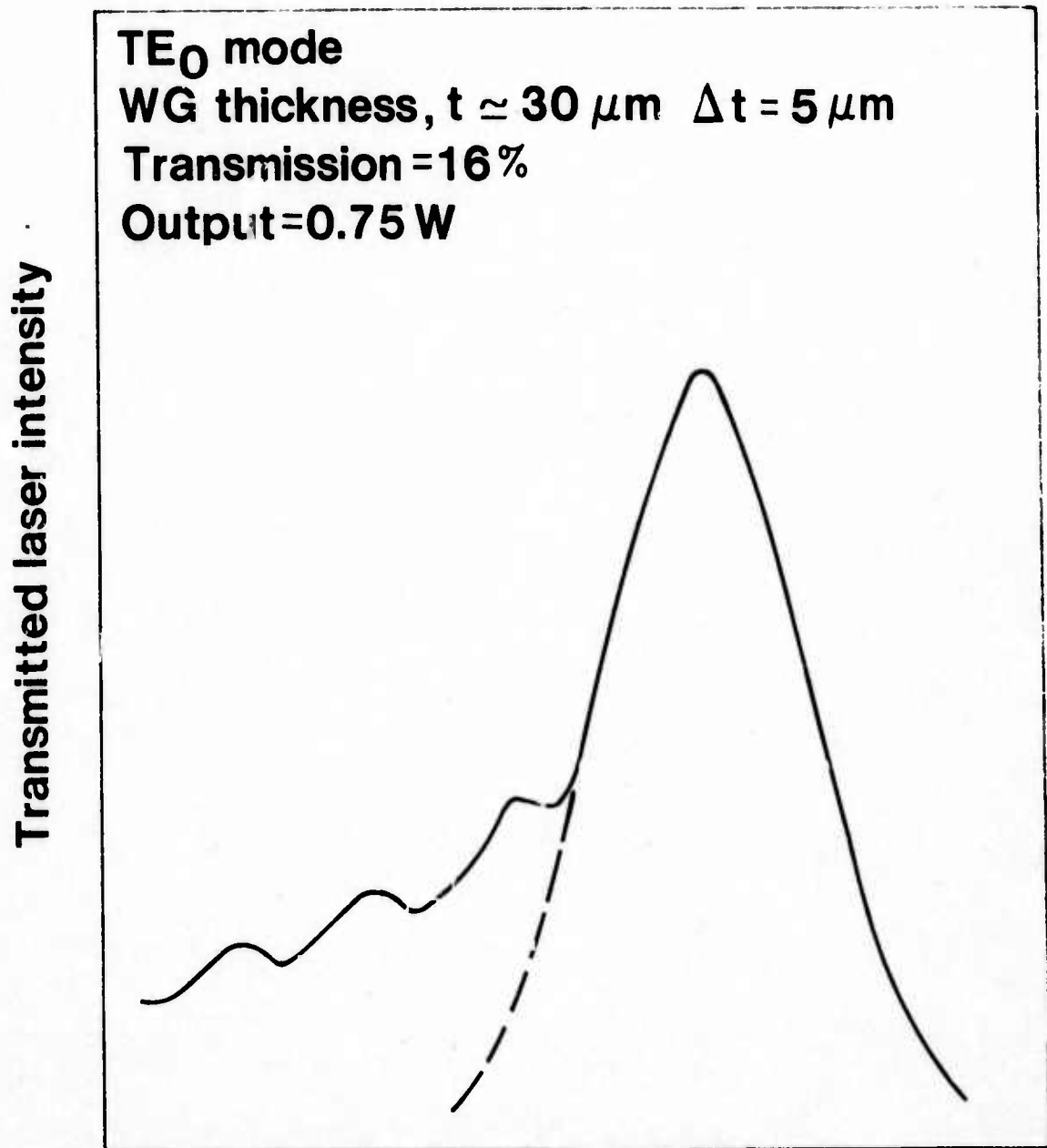
FIG. 6

radiative cooling from the copper base plate is sufficient. It is possible to further increase its power handling capability by circulating water through the copper block.

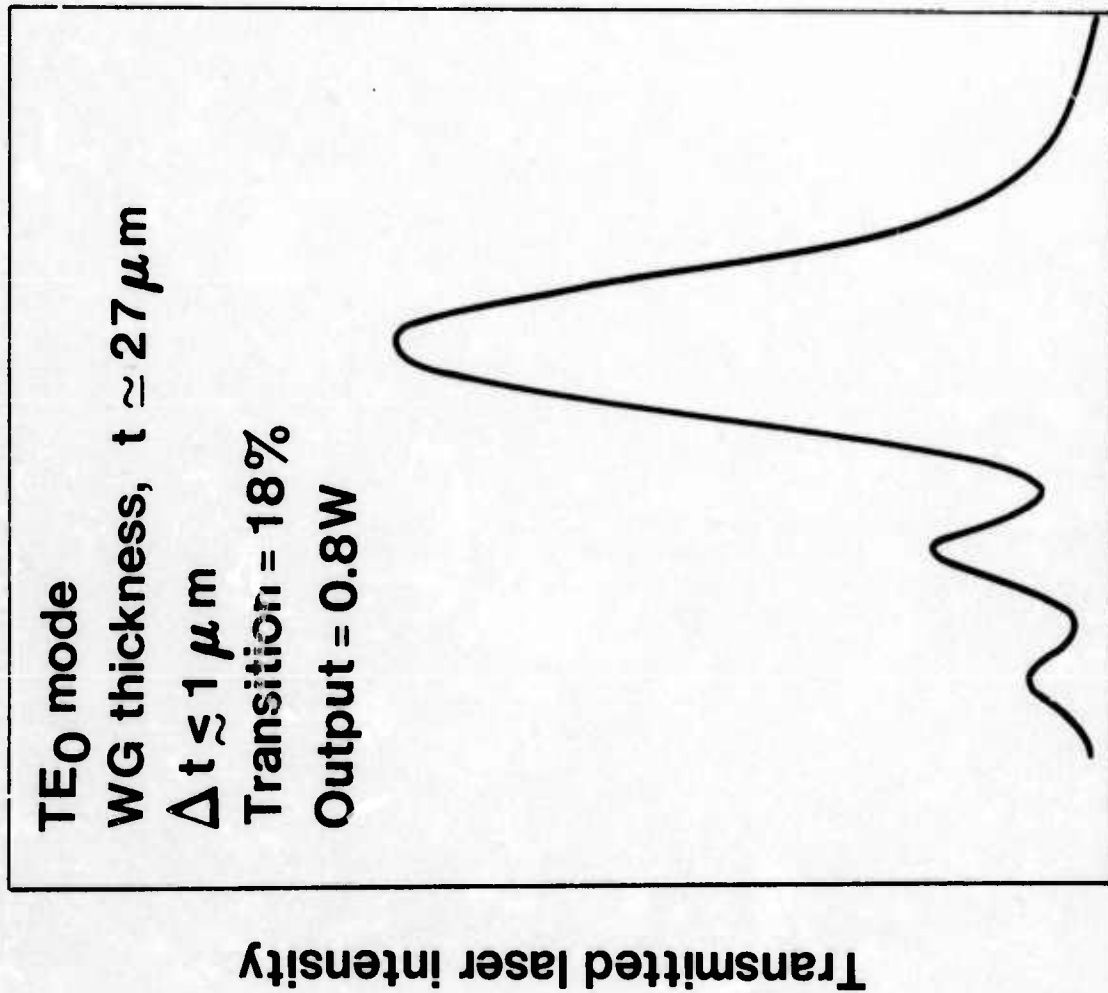
Measurements were also made of the far-field output beam profile. Figures 7 and 8 are the transmitted beam profiles obtained from sample B and sample C, respectively. Clearly the outcoupled beams in both cases are distorted but the extent of distortion varies with the quality of waveguides. The waveguide (Fig. 8) having a more uniformity in thickness yields a relatively better output beam profile in the far-field than the one (Fig. 7) having a relatively poor thickness uniformity. The beam divergence angles for both cases are about the same and it is a characteristic of the output coupling. The outcoupled beam quality, to some extent, is governed by the quality of waveguides. Accumulated experimental results so far seem to confirm this observation. Both coupling efficiency and beam quality appear to decrease with increasing waveguide tapering or wedging. Furthermore, if the condition for aperture matching is not exactly met, the outcoupled beam in general is not symmetric and, in fact, it is often found to be slightly elliptical. Since most of our experimental data were obtained for an input laser beam of 1 mm in diameter, which is one of the constraints imposed by microwave considerations, we found that the outcoupled beam shape is best for the TE_1 mode, consistent with our calculations as shown in Fig. 5.

Another often observed effect is the so-called "beam steering," which means that the direction of mode propagation in the waveguide has been altered. The steering angle increases with increasing mode order and the magnitude is typically in the milli-radians. In general, no measurable beam steering is observed for the TE_0 mode.

FAR FIELD LASER INTENSITY PROFILE (TE₀)



FAR FIELD LASER INTENSITY PROFILE (TE₀)



3.0 MICROWAVE CHARACTERISTICS OF IR WAVEGUIDE MODULATORS

3.1 Introduction

The microwave activities have resumed on the modulator shortly following recent significant progress on the optical coupling and on the fabrication of the bonded-down thin-slab GaAs structure. Previous work with the mini-gap ridge waveguide provided the information which justified carrying through another modulator experiment similar to that reported (Ref. 10) earlier on optical sideband generation. It was recognized at a very early (Ref. 2, 11) stage of the program that the free-standing waveguide modulator structure was not completely satisfactory because of its mechanical problems and lack of reproducibility in the microwave properties. For narrow band operation where the modulator is used as a resonator, reproducibility can be compensated for with conventional external microwave tuners. However, if broad band operation is desired, a traveling wave modulator structure must be used. In this case, broad band impedance transformations at the input of the very low impedance modulator transmission line must be carefully designed into the structure. Any additional tuning for improving the power transfer in general will reduce the bandwidth. For these reasons the improved waveguide fabrication technique to produce reproducible waveguides with tight tolerance will become increasingly important as the program progresses from the resonator modulator to the broad band structure. The improved fabrication technique which involves the precision thinning of the active GaAs slab after permanent bonding to a metal carrier greatly increases the survivability of GaAs waveguide when subjected to optical and microwave testing cycles. The technique has also resulted in greatly improved thickness control which is very important for establishing the correct values for the microwave characteristic impedances of the transmission lines, as well as for obtaining good transmitted laser beam profile.

Broad band operation of the modulator requires that a series of short transmission lines, connected in tandem have predetermined values for characteristic impedance and length. One approach is to use the accurate photolithographic techniques to obtain values of characteristic impedances by varying microstrip line widths. Another technique would be to fabricate accurate steps in ridge waveguides that can provide a broad band matching to the modulator. Still another technique would be to fabricate steps in a coaxial line that connects to the GaAs sample. All of these have been considered and a selection has been made for future experimental investigation. During this reporting period a number of newly fabricated microstrip lines have been evaluated. They are designed specifically for performing the sideband generation experiment. Also during this reporting period, a broad band structure has been considered and fabrication of an experimental model is in progress.

3.2 Studies of Microstrip Waveguide Modulator Configurations

Since great improvements were made on the optical transmission, plans are proceeding to immediately repeat the sideband generation experiment before the study of a broadband microwave circuit is completed. The modulator structure selected for this experiment is a microstrip resonator. The reason for this choice is based primarily on the existing information (Ref. 2) on this structure type. The advantage of using resonator type is that the modulator can be center fed through a short microstrip line, as shown in Fig. 4, with a high degree of confidence for reasonable impedance matching.

The microstrip construction consists of fabricating a narrow metallic conducting strip on the GaAs surface. The surface opposite to the microstrip is completely metallized to form a good ground plane. For most efficient modulator operation the width of the strip is made equal to that of the laser beam. Intimate contact to the GaAs surface is assured by evaporation and electro-plating of metallic layers with high degree of thickness accuracy. The chief disadvantage is that characteristic impedances decreases with increasing the microstrip line width that causes difficulty in microwave power transfer. Nevertheless, the microstrip approach provides a rugged structure and high power dissipation capability. It is believed that good heat conduction through the thin-slab GaAs waveguide to the copper support block is an important feature for making high power devices.

For evaluating the microwave properties, long straight microstrip lines were first fabricated and experimentally analyzed. The details of the connection to the end of the line are shown schematically in Fig. 9. The connection is made by modification of a commercially available connector that provides a very precised transition from a coaxial line to the microstrip. Measurements of resonant frequency were made for several lengths and for several samples when the end is open-circuited and the input resistance is at resonance. The sketch in Fig. 9 also shows the details and thicknesses of the various layers. It was found to be important that both the ground plane and the strip must be thicker than $10\text{ }\mu\text{m}$ to minimize microwave losses. In the course of this work several other connections were evaluated such as a coaxial line perpendicular to the GaAs surface and a simple miniature coax line parallel to the surface. Neither were found to be satisfactory.

The measured results at 16 GHz were:

$$\begin{aligned}\epsilon_{\text{eff}} &= 12.2 \\ \text{Attenuation} &= 0.75 \text{ db/cm} \\ n = \sqrt{\epsilon_{\text{eff}}} &= 3.5\end{aligned}$$

MICROWAVE CONNECTOR SCHEMATIC

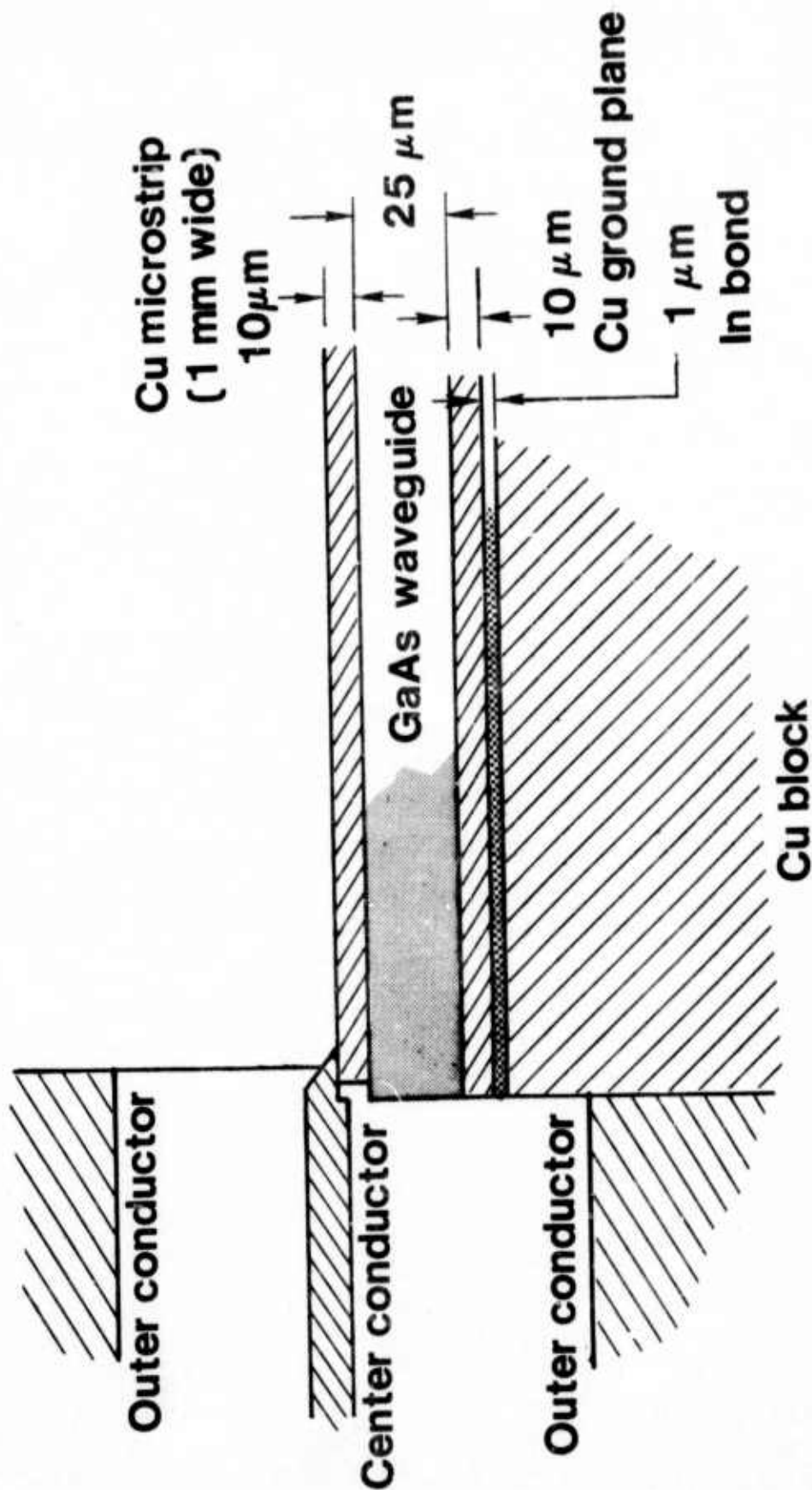


FIG. 9

RO9-176-1

These values compare favorably with values determined earlier for ridge waveguides (Ref. 2).

The characteristic impedance could not be determined accurately because of the lack of precision on measuring a small impedance value. A value of $Z_0 = 2.7$ ohms for 25 μm was estimated from an electrostatic model as follows:

$$Z_0 = 377 \frac{t}{W+2t}$$

where t is thickness of the GaAs waveguide and W is the width of the microstrip electrode. A photograph of a test line mounted in the test fixture is shown in Fig. 10. Great care was taken in the design to insure that the ground plane was not interrupted at the connector interface. Results of this preliminary investigation are useful for the design of a narrow-band microstrip modulator for the interim experiment. The sample to be used is resonant at 15.6 GHz and has an input resistance at the center tap point of 5.6 ohms as shown in Fig. 4. With two $\lambda/4$ impedance steps built into the microstrip input line, and a modified connection (a longer extension from the center indicator), an input resistance of approximately 25 ohms was measured at 15.6 GHz. At approximately 13 GHz an impedance of 40 ohms was measured. This degree of impedance matching is adequate for the interim modulation experiment.

3.3 Broadband Modulator Design

In the broadband phase of the work low loss becomes very important because the available microwave power is not unlimited. Since small flexible coaxial cables between the microwave source and the modulator can result in microwave losses as much as half its power, standard low loss rectangular waveguides will best be used. It therefore makes sense to design a direct transition from waveguide to the microstrip modulator. This can best be done with a series of steps in a ridge waveguide. This approach in principle also allows a broadband transition to dimensions close to those of the waveguide modulator microstrip. A sketch of such a transition is shown schematically in Fig. 11. A preliminary design has been completed and a testing structure is being fabricated. Because of the precision-ground mating surface lateral movement of the ridge will be necessary for making minor adjustments. The ridge, though the details are not shown in Fig. 11, will have sufficient pressure to maintain a close contact without damaging the GaAs sample.

EXPERIMENTAL MICROWAVE CONNECTOR

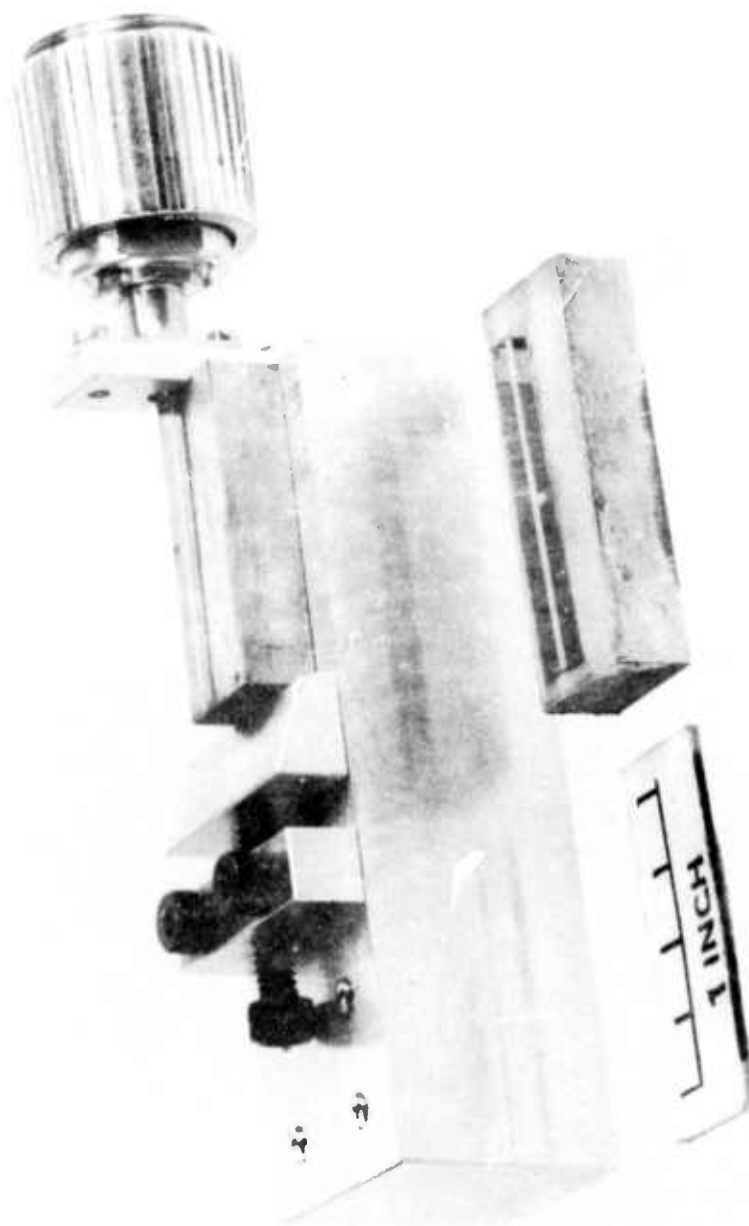


FIG 10

RO9-176-5



SCHEMATIC OF BROADBAND MICROWAVE CONNECTOR

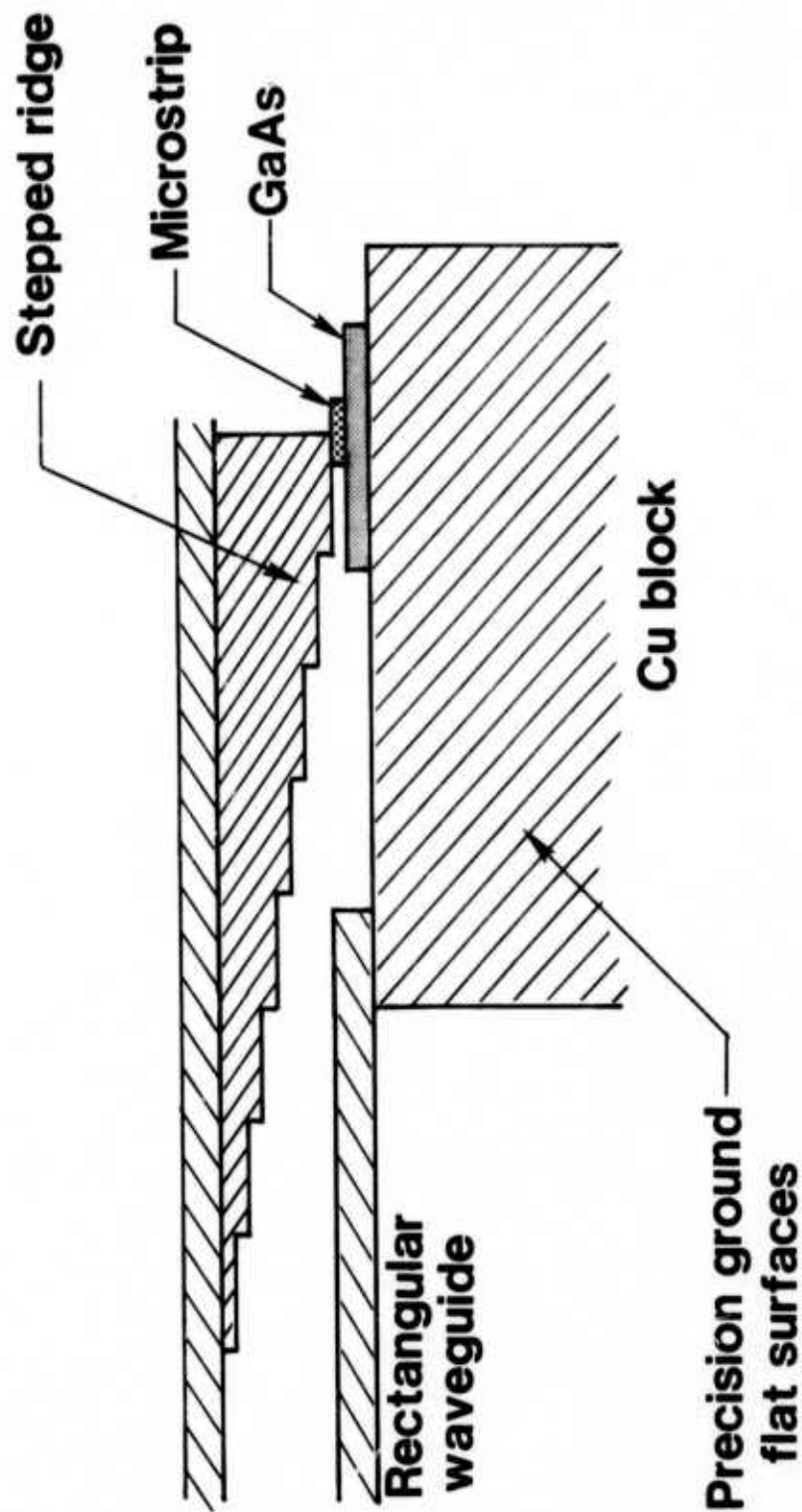


FIG. 11

RO9-176-6



4.0 OPTICAL AND MICROWAVE INTERFACE

4.1 Introduction

In Sections 2.0 and 3.0 we have examined the characteristics of optical and microwave waveguide modulators separately. To combine these two technologies into one practical and compatible hardware for broadband frequency chirping of a CO₂ laser beam it has been a rather difficult task ever since the start of this program. There have been many trade-offs and adjustment on both sides to accommodate each other. This section presents a modulator configuration which provide the necessary interface of the two aspects. This configuration is by no means the final version and is designed primarily for carrying out a second demonstration of side band power generation of a CO₂ laser at the Ku-band. It is only for this reason that this configuration represents the best approach.

Since our first demonstration of microwave modulation of CO₂ laser (Refs. 10, 11) by means of infrared waveguides, there have been several significant breakthroughs in both optical and microwave modulator development as evident from the results of previous sections. The observed sideband power of our first attempt in 1973 was barely resolvable by the infrared Fabry-Perot interferometer and the sideband power was estimated at a level between 50 to 100 micro-watts. Two major reasons for such low level sideband power generation in our first attempt are (1) low optical transmission and (2) short propagation length. Waveguide modulators, as presented below, yield typically a total optical transmission of ≈ 20 percent over a propagation length of ≥ 2.8 cm. These results represent an overall improvement of at least 50 times.

4.2 Waveguide Modulator Assembly

Most all of the components required to generate optical sideband power at 16 GHz with the new modulator configuration are completed and the experiment is presently being carried out. The active medium is made of the sample D as listed in Table I. Before processing the microstrip line, as shown in Fig. 4, the optical transmission characteristic of this waveguide has been thoroughly examined. The apparatus used in performing optical evaluation of all bonded waveguides is shown in Fig. 12. It consists of two precision-machined wedges placed in a housing. The top wedge is made to slide on the surface of the other by means of the micrometer drive. In this way the waveguide and prisms can be moved up or down with precision and control. Uniform pressure is applied to the flat top of these two identical prisms as they rise against top plates (not shown in Fig. 12).

After optical evaluation, a microstrip transmission line is processed on the top surface of the waveguide. It is then subjected to microwave testing with the special fixture as shown in Fig. 13. This fixture has the identical design features

**Best Available
Copy
for FIG. 12**

FIG. 12

ROG-176-3



RED WAVEGUIDE
ASSEMBLY

MICROWAVE CONNECTOR FOR GaAs WAVEGUIDE MODULATOR

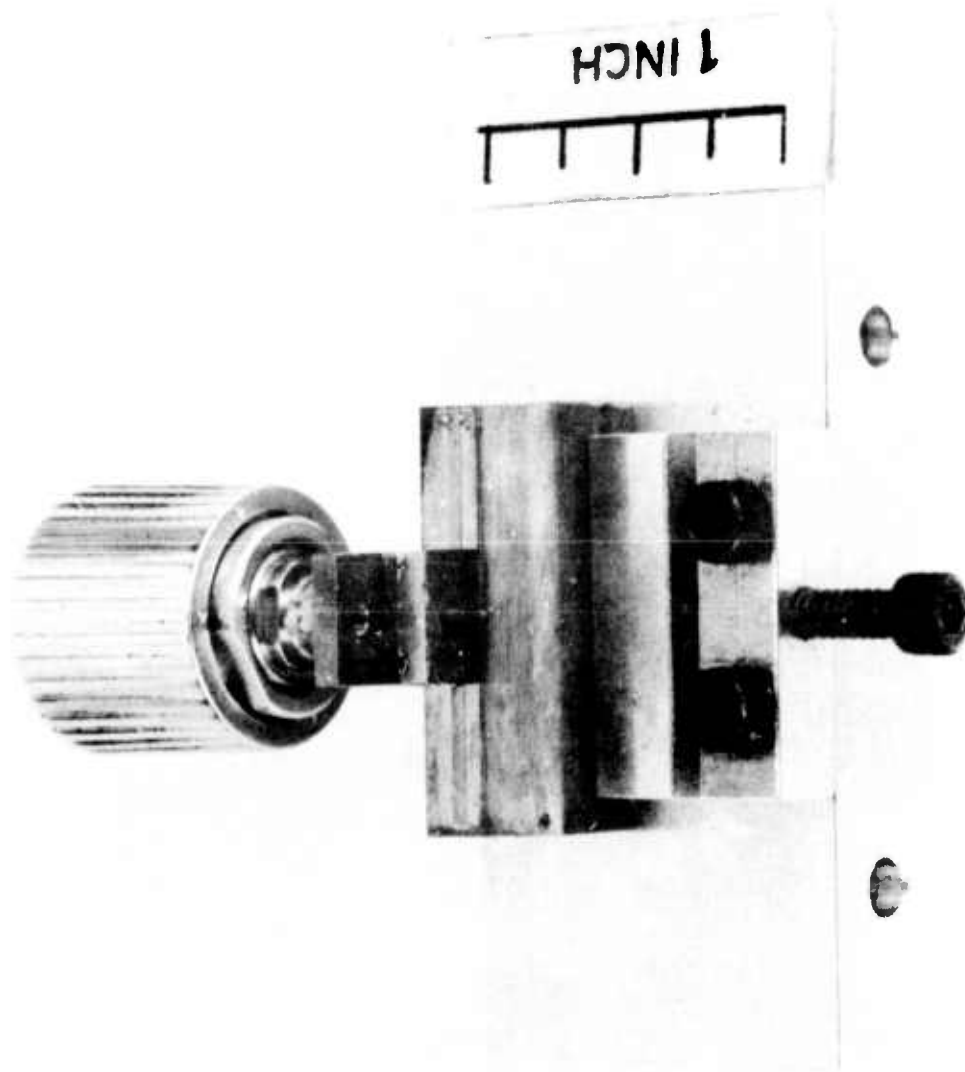


FIG. 13

as the one shown in Fig. 10, with the exception that this fixture is made to fit the modulator housing (Fig. 12). The entire modulator assembly including the top covering plates is shown in Fig. 14.

In addition to the waveguide modulator as shown in Fig. 4, several waveguides with similar properties are being fabricated as the back-ups for the interim experiment. The waveguide modulator element has a T-shape microstrip line having a length of 2.7 cm, and a width of 0.1 cm. The microwave coupling will be similar to that shown in Fig. 9. A microwave source will deliver an input power of 20 watts at Ku-band and a CO₂ laser will have an input optical power of 6 watts.

From the expression (3) for calculating the optical phase-shift as presented in our earlier (Ref. 11) work, we estimate that a sideband power of about 6 mW can be obtained under above described conditions. More enhancement in the sideband power generation can be gained by increasing either or both the optical and the microwave power with the present waveguide modulator structure. The results of this interim experiment and further development of a laboratory model of broadband traveling wave ridge waveguide modulators suitable for high power application will be reported in the next technical report.

INFRARED WAVEGUIDE MODULATOR ASSEMBLY

Top view

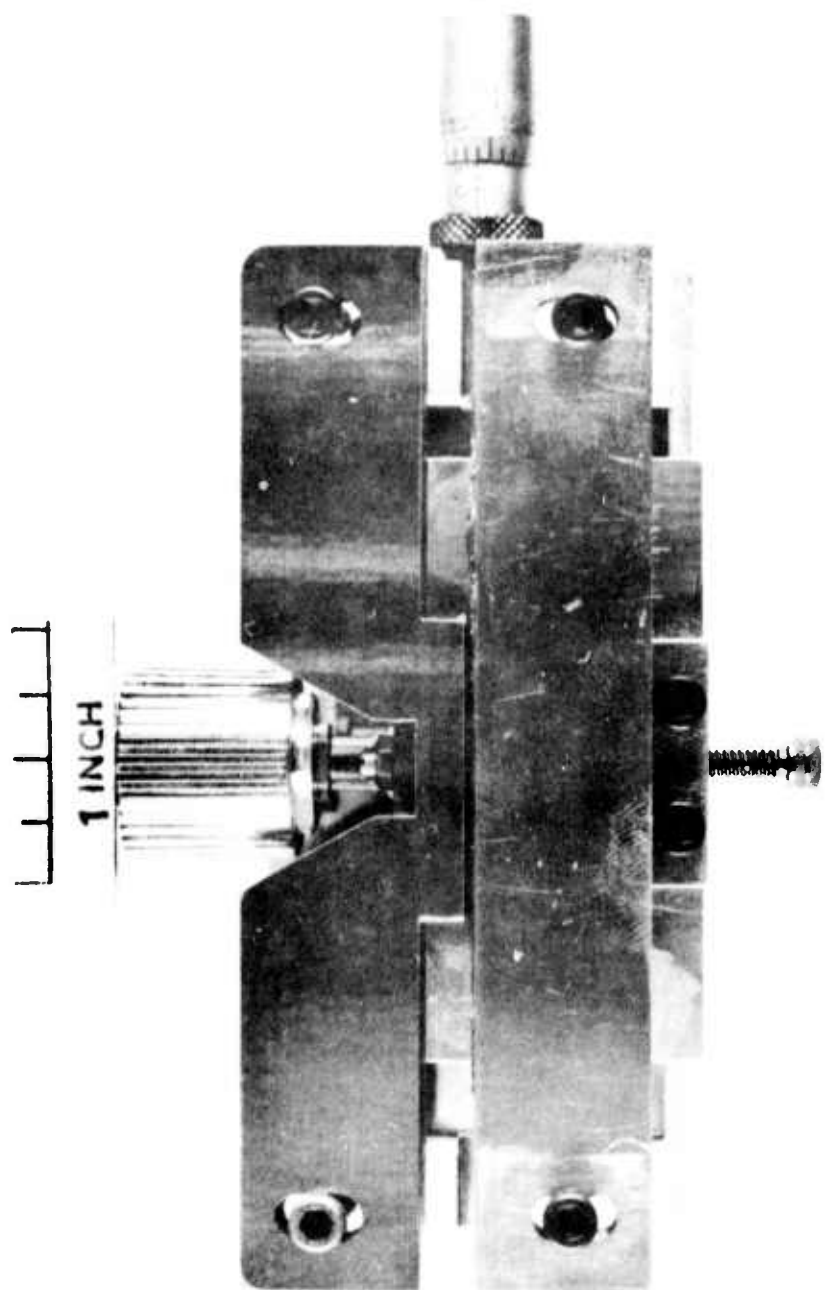


FIG. 14

REFERENCES

1. Cheo, P.K., D.W. Fradin, and R. Wagner,: Microwave Waveguide Modulators For CO₂ Lasers, Fifth Semi-Annual Technical Report Contract No. N00014-73-C-0087, March 1975.
2. Cheo, P.K., M. Gilden, D.W. Fradin, and R. Wagner,: Microwave Waveguide Modulators for CO₂ Lasers, Fourth Semi-Annual Technical Report Contract N00014-73-C-0087, September 1974.
3. Ogawa, K., et al, IEEE J. Quant. Elect. QE-9, 29 (1973).
4. Tang, C.L., Cornell University (private communication).
5. Cheo, P.K., et al; Ultra Wideband Thin Film Modulator for CO₂ Lasers, 2nd Semi-Annual Technical Report Contract No. N00014-73-C-0087, September 1973.
6. Bennett, G.A., and R.B. Wilson, J. Scientific Inst. 43, 669 (1966).
7. Wilson, R.B., J. Scient. Inst., 44 (1967).
8. Tien, P.K., and R. Ulrich, J. Opt. Soc. Am. 60, 1325 (1970).
9. Cheo, P.K., et al, Appl. Opt. 12, 500 (1973).
10. Cheo, P.K., Thin Film Waveguides and Devices for Lasers, Top. Meeting on Integrated Optics, New Orleans, January 1974, Paper MA6 (invited).
11. Cheo, P.K., and M. Gilden, Appl. Phys. Lett. 25, 272 (1974).

Office Of Naval Research Department of the Navy Attn: Physics Program Arlington, Virginia 22217	3 copies
Naval Research Laboratory Department of the Navy Attn: Technical Library Washington, D. C. 20375	1 copy
Office of the Director of Defense Research and Engineering Information Office Library Branch The Pentagon Washington, D. C. 20301	1 copy
U. S. Army Research Office Box CM Duke Station Durham, North Carolina 27706	1 copy
Defense Documentation Center Cameron Station Alexandria, Virginia 22314	12 copies
Defender Information Analysis Center Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201	1 copy
Director Office of Naval Research Branch Office 536 South Clark Street Chicago, Illinois 60615	1 copy
San Francisco Area Office Office of Naval Research 760 Market Street, Room 447 San Francisco, California 94102	1 copy
Air Force Office of Scientific Research Department of the Air Force Washington, D. C. 22209	1 copy

Office of Naval Research Branch Office Attn: Dr. Robert Behringer 1030 East Green Street Pasadena, California 91106	1 copy
Code 102 1P (ONRL) Office of Naval Research 800 N. Quincy Street Arlington, Virginia 22217	6 copies
Defense Advanced Research Projects Agency 1400 Wilson Blvd. Arlington, Virginia 22209 Attn: Director, Laser Division Dr. P. Clark	2 copies
ODDR&E Pentagon Washington, D. C. 20301 Attn: Ass't. Dir. (Space and Advanced Systems)	1 copy
Office of the Ass't Secretary of Defense System Analysis (Strategic Programs) Washington, D. C. 20301 Attn: Mr. Gerald R. McNichols	1 copy
U.S. Arms Control and Disarmament Agency Dept. of State Bldg., RM 4931 Washington, D. C. 20451 Attn: Dr. Charles Henkin	1 copy
Energy Research Development Agency Division of Military Applications Washington, D. C. 20545	1 copy
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135 Attn: Dr. John W. Dunning, Jr. (Aerospace Res. Engineer)	1 copy
National Aeronautics & Space Administration Code RR, FOB 10B 600 Independence Ave. SW Washington, D. C. 20546	1 copy

National Aeronautics and Space Administration
Ames Research Center

Moffet Field, California 94035

Attn: Mr. Robert L. McKenzie

1 copy

Dr. Kenneth W. Billman

1 copy

Department of the Army

Office of the Chief of RD&A

Washington, D. C. 20310

Attn: DARD-DD

1 copy

DAMA-WSM-T

1 copy

Department of the Army

2 copies

Office of the Deputy Chief of Staff

for Operations & Plans

Washington, D. C. 20310

Attn: DAMO-RQD

Ballistic Missile Defense Program Office (BMDPO)

3 copies

The Commonwealth Bldg.

1300 Wilson Blvd.

Arlington, Virginia 22209

Attn: Mr. Albert J. Bast, Jr.

U. S. Army Missile Command

2 copies

Research and Development Division

Redstone Arsenal, Alabama 35809

Attn: Army High Laser Energy Programs

Commander

1 copy

Rock Island Arsenal

Rock Island, Illinois 61201

Attn: SARRI-LR, Mr. J. W. McGarvey

Commanding Officer

1 copy

U.S. Army Mobility Equipment R&D Center

Ft. Belvoir, Virginia 22060

Attn: SMLFB-MV

Commander

1 copy

U. S. Army Armament Command

Attn: AMSAR-RDT

Rock Island, Illinois 61201

Director
Ballistic Missile Defense Advanced Technology Center
P. O. Box 1500
Juntsville, Alabama 35807
Attn: ATC-0 1 copy
ACT-T 1 copy

Commander
U. S. Army Material Command
Alexandria, Virginia 22304
Attn: Mr. Paul Chernoff (AMCRD-T) 1 copy
Dr. B. Zarwyn (AMCRD-T) 1 copy

Commanding General 1 copy
U. S. Army Nuntions Command
Dover, New Hampshire 07801
Attn: Mr. Gilbert F. Chesnov (AMSMU-R)

Director
U. S. Army Ballistic Res. Lab
Aberdeen Proving Ground, MD 21005
Attn: Dr. Robert Eichelberger 1 copy
Mr. Frank Allen 1 copy
Dr. E. C. Alcares 1 copy

Commandant
U. S. Army
Air Defense School
Ft. Bliss, Texas 79916
Attn: Air Defense Agency 1 copy
ATSA-CTD-MS 1 copy

Commanding General
U. S. Army Combat Dev. Command
Ft. Belvoir, Virginia 22060
Attn: Director of Material, Missile D'v. 1 copy

Commander 1 copy
U. S. Army Training And Doctrine Command
Attn: ATCD-CF
Ft. Monroe, Virginia 23651

Commander 1 copy
U. S. Army Frankford Arsenal
Philadelphia, Pennsylvania 19137
Attn: Mr. M. Elnick SARFA-FCF
Bldg. 201-3

Commander 1 copy
U. S. Army Electronics Command
Ft. Monmouth, New Jersey 07703
Attn: AMSEL-CT-L, Dr. R. G. Buser

Commander 1 copy
U. S. Army Combined Arms Combat
Developments Activity
Ft. Leavenworth, Kansas 66027

National Security Agency 1 copy
Ft. Geo. G. Meade, Maryland 20755
Attn: R. C. Foss A763

Deputy Commandant for Combat & 1 copy
Training Developments
U. S. Army Ordnance Center and School
Attn: ATSL-CTD-MS-R
Aberdeen Proving Ground, Maryland 21005

Commanding Officer 1 copy
USACDC CBR Agency
Ft. McClellan, Alabama 36201
Attn: CDCCBR-MR (Mr. F. D. Poer)

Department of the Navy 1 copy
Office of the Chief of Naval Operations
Pentagon 5C739
Washington, D. C. 20350
Attn: (OP 982F3)

Office of Naval Research
Attn: Dr. Fred Quelle 1 copy
Dr. M. White 1 copy
495 Summer Street
Boston, Massachusetts 02210

Department of the Navy 1 copy
Deputy Chief of Naval Material (Dev.
Washington, D. C. 20360
Attn: Mr. R. Gaylord (MAT 032B)

Naval Missile Center
Point Mugu, California 93042
Attn: Gary Gibbs (Code 5352) 1 copy

Naval Research Lab
Washington, D. C. 20375
Attn: (Code 5503-LTP0)
Dr. P. Livingston (Code 55060) 1 copy
Dr. A. I. Schindler (Code 6330) 1 copy
Dr. H. Shenker (Code 6530) 1 copy
Mr. D. J. McLaughlin (Code 5560) 1 copy
Dr. John L. Walsh (Code 5503) 1 copy

High Energy Laser Project Office 1 copy
Department of the Navy
Naval Sea Systems Command
Washington, D. C. 20360
Attn: Capt. J. G. Wilson, USN (PMS-405)

Superintendent 1 copy
Naval Postgraduate School
Monterey, California 93940
Attn: Library (Code 2124)

Navy Radiation Technology Liaison Office 1 copy
Air Force Weapons Lab. (NLO)
Kirtland AFB, New Mexico 87117

Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910
Attn: Dr. Leon H. Schindel (Code 310) 1 copy
Dr. E. Leroy Harris (Code 313) 1 copy
Mr. K. Enkenhus (Code 034) 1 copy
Mr. J. Wise (Code 047) 1 copy

U. S. Naval Weapons Center
China Lake, California 93555
Attn: (Code 5114) 1 copy
Technical Library 1 copy

HQ USAF (AF/RDFS) 1 copy
Pentagon
Washington, D. C. 20330
Attn: Lt. Col. A. J. Chiota

HQ AFSC/XRLW 1 copy
Andrews AFB
Washington, D. C. 20331
Attn: Maj. J. M. Walton

HQ AFSC (DLCAW) Andrews AFB Washington, D. C. 20331 Attn: Maj. H. Axelrod	1 copy
Air Force Weapons Lab Kirtland AFB, New Mexico 87117 Attn: LR AL	4 copies 2 copies
HQ SAMSO (SRTD) P. O. Box 92960, Worldway Postal Center Los Angeles, California 90009 Attn: Lt. Dorian DeMaio (XRTD)	1 copy
AF Avionics Lab (TEO) Wright Patterson AFB, Ohio 45433 Attn: Mr. K. Hutchinson	1 copy
Dept. of the Air Force Air Force Materials Lab. (AFSC) Wright Patterson AFB, Ohio 45433 Attn: Maj. Paul Elder (LPS) Laser Window Group	1 copy
HQ Aeronautical Systems Division Wright Patterson AFB, Ohio 45433 Attn: XRF - Mr. Clifford Fawcett	1 copy
Rome Air Development Command Griffiss AFB Rome, New York 13440 Attn: Mr. R. Urtz (OCSE)	1 copy
HQ Electronics Systems Div. (ESL) L. G. Hanscom Field Bedford, Massachusetts 01730 Attn: Mr. Alfred E. Anderson (XRT) Capt. James C. Jalbert (XRJ) Technical Library	1 copy 1 copy 1 copy
Air Force Rocket Propulsion Lab Edwards AFB, California 93523 Attn: B. R. Bornhorst, (LKCG)	1 copy

Air Force Aero Propulsion Lab
Wright Patterson AFB, Ohio 45433
Attn: Col. Walter Moe (CC) 1 copy

Dept. of the Air Force
Foreign Technology Division
Wright Patterson AFB, Ohio 45433
Attn: PDTW 1 copy

CINCSAC/INEP
Offutt AFB, Nebraska 68113 1 copy

Commandant of the Marine Corps.
Scientific Advisor (Code RD-1)
Washington, D. C. 20380 1 copy

USAF/INARA
Washington, D. C. 20330
Attn: Lt. Col. W. M. Truesdell 1 copy

Aerospace Research Labs., (AP)
Wright Patterson AFB, Ohio 45433
Attn: Lt. Col. Max Duggins 1 copy

Defense Intelligence Agency
Washington, D. C. 20301
Attn: Mr. Seymour Berler (DTIB) 1 copy

Central Intelligence Agency
Washington, D. C. 20505
Attn: Mr. Julian C. Nall 1 copy

Analytic Services, Inc.
5613 Leesburg Pike
Falls Church, Virginia 22041
Attn: Dr. John Davis 1 copy

Aerospace Corp.
P. O. Box 92957
Los Angeles, California 90009
Attn: Dr. G. P. Millburn 1 copy

Massachusetts Institute of Technology
Lincoln Lab - P. O. Box 73
Lexington, Massachusetts 02173
Att: Dr. R. Kingston 1 copy
Dr. P. Ingwersen 1 copy
Dr. W. E. Bicknell 1 copy